

# Military medical revolution: Deployed hospital and *en route* care

Lorne H. Blackbourne, MD, David G. Baer, PhD, Brian J. Eastridge, MD, Evan M. Renz, MD, Kevin K. Chung, MD, Joseph DuBose, MD, Joseph C. Wenke, PhD, Andrew P. Cap, MD, Kimberlie A. Biever, MS, Robert L. Mabry, MD, Jeffrey Bailey, MD, Christopher V. Maani, MD, Vikhyat Bebarta, MD, Todd E. Rasmussen, MD, Raymond Fang, MD, Jonathan Morrison, MD, Mark J. Midwinter, MD, Ramón F. Cestero, MD, and John B. Holcomb, MD

## INTRODUCTION

The battlefield has seen tremendous revolutions in military medical affairs (RMMAs) as a result of the last decade of continuous combat operations. The advances in deployed and *en route* combat casualty care are categorized as individual RMMAs shown in Table 1. As with prehospital advances, the basis for many of the RMMAs in the deployed hospital care environment as well as *en route* care was translated from civilian trauma practice but is realistic and relevant to the battlefield context. As the conflict evolved, the substantive data from the battlefield led to many new paradigms of treatment and evacuation. The successful implementation of many of these battlefield practices was then effectively translated back into the civilian injury care environment as has been typical of medical advances developed subsequent to previous conflicts of antiquity.

The RMMAs that occurred during the last 10 years of combat casualty care are in the realm of deployed hospital care and *en route* care and are discussed in detail in this article.

## DEPLOYED HOSPITAL CARE

### Global Combat Damage-Control Surgery

Damage-control surgery is well established in civilian trauma centers and is described as the trilogy of abbreviated operation, intensive care stabilization/resuscitation, and the return to the operating room for the last or multistage procedures for the definitive surgical repair. This paradigm has reduced mortality

for the patient population with severe abdominal injuries<sup>1</sup> and has gained widespread acceptance. In the civilian trauma systems, this trilogy usually occurs in one hospital. This approach has been described for all anatomic injuries in the severely injured patient at risk for physiologic decompensation.<sup>2,3,4</sup>

In contrast to the civilian damage control, global combat damage-control surgery often involves multiple separate surgical facilities, multiple surgeons, multiple resuscitation and stabilization episodes, helicopter evacuation, and fixed-wing evacuations by the Critical Care Air Transport Team (CCATT) during a multistage global transit (Fig. 1).<sup>4-5</sup>

Global combat damage control has been successfully conducted for thousands of combat-wounded patients within a matter of several days and represents a profound revolutionary change in the care of patients severely wounded in combat.

### Damage-Control Resuscitation

Damage-control resuscitation (DCR) is one of the most significant RMMAs to develop from the overseas contingency operations (OCO) in Iraq and Afghanistan. As introduced in a 2007 special commentary by Holcomb et al.,<sup>6</sup> DCR is described as “a structured intervention [which] begins immediately after rapid initial assessment in the ED and progresses through the OR into the ICU. All efforts are directed towards this goal of preventing/correcting hypothermia, acidosis, and coagulopathy by repeated point of care testing and the use of multiple blood products and drugs readily available in theater, albeit in new ratios and amounts.” DCR consists of two major efforts as follows: permissive hypotension to prevent excessive bleeding and hemostatic resuscitation, which stresses the administration of blood products in a 1:1:1 manner.<sup>5</sup>

Most trauma patients are not coagulopathic and do not require blood product resuscitation. However, up to 25% of severely bleeding trauma patients present with acute coagulopathy, and mortality in these patients can be as high as 50%. During the course of the last decade, the US military medical community has developed the concept of DCR to treat this subset of critically injured patients. This revolutionary change improved doctrine developed in the latter half of the 20th century.

The cornerstone of the DCR revolution is the aggressive use of blood products including packed red blood cells (PRBCs), fresh frozen plasma (FFP), and platelets in ratios near 1:1:1. Military studies conducted during the Iraq war suggested that

From the US Army Institute of Surgical Research (L.H.B., D.G.B., B.J.E., E.M.R., K.K.C., J.C.W., A.P.C., K.A.B., R.L.M., J.B., C.V.M., T.E.R.); MEDCOM (V.B.), Brooke Army Medical Center, Fort Sam Houston; US Navy (R.F.C.), Naval Medical Research Unit San Antonio, San Antonio; University of Texas Health Science Center at Houston (J.B.H.), Houston, Texas; Baltimore Center for the Sustainment of Trauma and Readiness Skills (CSTARS) (J.D.), University of Maryland Medical Center, Baltimore, Maryland; US Air Force (R.F.), Landstuhl Regional Medical Center, Landstuhl, Germany; and Royal Centre for Defence Medicine (JM, M.J.M.), Birmingham, United Kingdom.

The opinions or assertions contained herein are the private views of the author and are not to be construed as official or as reflecting the views of the US Department of the Army, Navy, or Air Force or the US Department of Defense.

Address for reprints: Lorne H. Blackbourne, MD, US Army Institute of Surgical Research, Fort Sam Houston, TX 78234-6315; email: lorne.h.blackbourne@us.army.mil.

DOI: 10.1097/TA.0b013e3182754900

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>01 DEC 2012</b>		2. REPORT TYPE <b>N/A</b>		3. DATES COVERED <b>-</b>	
4. TITLE AND SUBTITLE <b>Military medical revolution: deployed hospital and en route care</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) <b>Blackbourne L. H., Baer D. G., Eastridge B. J., Renz E. M., Chung K. K., Dubose J. J., Wenke J. C., Cap A. P., Biever K. A., Mabry R. L., Bailey J., Maani C. V., Bebart V. S., Rasmussen T. E., Fang R., Morrison J. J., Midwinter M. J., Cestero R. F., Holcomb J. B.,</b>				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>United States Army Institute of Surgical Research, JBSA Fort Sam Houston, TX</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release, distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>UU</b>	18. NUMBER OF PAGES <b>10</b>	19a. NAME OF RESPONSIBLE PERSON
a REPORT <b>unclassified</b>	b ABSTRACT <b>unclassified</b>	c THIS PAGE <b>unclassified</b>			

**TABLE 1.** RMMAs, 2001 to 2011 OCOs in Afghanistan and Iraq.

OCO	RMAA
Deployed hospital care	DCR
	Diagnostic evaluation for explosion injury
	Vascular surgery
	Ortho wound care
	Regional anesthesia and TIVA
	Combat burn care
	Management of TBI
	Surgical intervention for penetrating TBI
	Negative-pressure combat wound dressings
	Intravenous TXA
	Far-forward MIS
	Coagulation monitoring with thromboelastography/RoTEM
En route care	Global <i>en route</i> care (CCATT and Burn Flight Team)
	<i>En route</i> critical care nursing
	US Army flight medic training

patients receiving higher ratios of FFP to PRBCs had lower mortality rates (19% vs. 65%) compared with those who received lower ratios (1:8).<sup>6</sup> Similar results have been found in the civilian setting, where a retrospective analysis of patients receiving massive transfusions found a lower mortality (26% vs. 87.5%) in those who received FFP/PRBC in a higher ratio.<sup>7</sup> Current military DCR clinical practice guidelines (CPGs) state that, “The goal of transfusion of the patient with need for massive transfusion is to deliver a ratio of PRBCs to plasma to platelets of 1:1:1.”<sup>8</sup> As soon as patients arrive to the emergency department and are identified as likely to require massive transfusion, the DCR protocol is initiated; thawed plasma is used as a primary resuscitation fluid in a 1:1 ratio with PRBCs. This process continues through the operating room and into the intensive care unit. Crystalloid use is thereby significantly limited, as are other resuscitative adjuncts such as cryoprecipitate and tranexamic acid (TXA).

### TXA in Trauma Resuscitation

The landmark CRASH-2 trial testing the safety and efficacy of TXA in trauma resuscitation marked a turning point in the treatment of trauma patients. For the first time, a single pharmaceutical intervention was shown to reduce mortality in hemorrhaging trauma patients. This study documented the benefit of TXA in real-world clinical practice across a wide variety of settings, including austere environments. Reinforcing the revolutionary findings of CRASH-2, an analysis of early use of TXA by United Kingdom physicians at the North Atlantic Treaty Organization Role 3 Bastion hospital in Afghanistan documented similar results in combat casualties.<sup>9</sup> In this study of 896 casualties, 32.7% (n = 293) received TXA, while 67.2% (n = 603) did not. The patients receiving TXA had a higher survival rate (82.6% vs. 76.1%;  $p = 0.028$ ) than the massive transfusion

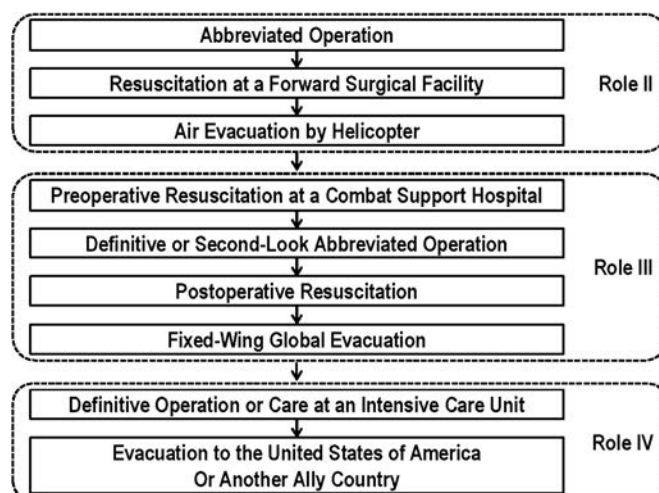
subgroup receiving TXA (28.1% vs. 14.4%;  $p = 0.004$ ). Multivariate regression modeling of the massive transfusion cohort showed that TXA use was independently associated with survival (odds ratio [OR], 7.28; 95% confidence interval [CI], 3.02–17.32). TXA is the first targeted therapy to be proven effective in hemorrhaging trauma patients, and CRASH-2 provides Level I evidence to support its use. TXA has been incorporated into the Joint Trauma System CPG for DCR and has been recommended as an option prehospital by the Committee on Tactical Combat Casualty Care and the Defense Health Board (DHB memo, TXA).

### Diagnostic Evaluation for Explosion Injury

Current practice for evaluating and treating penetrating injury to the abdomen, flank, and pelvis has undergone a drastic and profound change during OCOs. From World War I until 2004, a tenet of military surgery was to explore all patients with abdominal penetrating injury.<sup>10–12</sup> The advent of computed tomographic (CT) scan on the battlefield in Role 3 facilities has allowed visualization of the position of metallic fragments in penetrating abdominal injury patients. Beekley et al.<sup>13</sup> describe the successful nonoperative treatment of up to 60% of stable patients with penetrating fragments to the abdomen in the absence of frank peritoneal signs on physical examination and no intraperitoneal or retroperitoneal penetration of the fragments. With an available CT scanner, the mandate of surgical exploration for all penetrating abdominal wounds has been abandoned. The CT scanner has thus successfully revolutionized the care of combat wounded with penetrating abdominal injuries by avoiding iatrogenic morbidity associated with negative exploratory laparotomies.

### Vascular Surgery

The revolution in vascular injury management during the wars in Afghanistan and Iraq has at its core the resolute joining of combat-wounded patients with surgeons soon after the time of injury. This paradigm has been sustained because of a combination of life-preserving tactical combat casualty care, strategic positioning of forward surgical capability, and use of rapid



**Figure 1.** Global combat damage-control surgery.

medical evacuation (MEDEVAC) within a Joint Trauma System. This model of uniting a salvageable patient with a surgeon at a capable facility minutes after injury represents a profound change in how vascular trauma is managed. Evidence of this new paradigm is found in epidemiologic studies that report the rate of vascular injury on the modern battlefield to be five to six times higher than the rate reported in previous wars.<sup>14–16</sup> These studies capture the phenomenon of patients surviving to arrive at surgical facilities to have their injuries recorded and treated. Furthermore, for the first time in modern war, many of these decisions are made by surgeons with subspecialty vascular and cardiovascular training.<sup>17</sup>

Within this new paradigm, the revolution of military medical affairs as they pertain to vascular disruption, hemorrhage, and/or ischemia on the battlefield encompasses the following: forward deployment of subspecialty trained peripheral vascular surgeons,<sup>15,17</sup> definition of a neuromuscular ischemic threshold of the limb (<5 hours),<sup>18,19</sup> the need for expedited reperfusion following extremity vascular injury and ischemia,<sup>20,21</sup> reconstruction of vascular injury using saphenous vein as the conduit of choice,<sup>15,20</sup> repair of proximal watershed extremity vein injuries,<sup>15,22</sup> ligation of select minor or distal extremity vascular injuries (arterial and venous),<sup>14,23</sup> necessity of viable tissue coverage of vascular reconstruction to prevent disruption,<sup>24,25</sup> temporary shunts as an adjunct to accomplish reperfusion or venous outflow rapidly,<sup>26–28</sup> endovascular techniques to treat select patterns of vascular injury or disruption,<sup>29,30</sup> and endovascular balloon occlusion as a hemorrhage control or resuscitation adjunct.<sup>31–33</sup>

These advances made during the decade of war in Afghanistan and Iraq have been a result of the modern paradigm in which a salvageable patient is evacuated to a surgeon at a capable facility within minutes after injury. In aggregate, these advances represent a profound change in how vascular injury is managed in modern combat.

## Orthopedics

Like other aspects of casualty care, orthopedic surgery has profoundly changed since the Vietnam War. Since 82% of all soldiers wounded in action not returning to duty have at least one extremity injury, these changes have a significant impact on battle casualties.<sup>34</sup> Damage-control orthopedics refers to an approach that is designed to not place the most severely injured patients at further risk by aggressive early total care. The common practice is early, rapid, temporary stabilization of a fracture to minimize blood loss, then physiologic stabilization, and finally definitive orthopedic management.<sup>35</sup> The steps in this practice have been shown to be successful for unstable patients. The practice of combat damage control orthopedics is a necessity for virtually all extremity injuries and not just for soldiers who are in extremis. Temporary external fixation is the most common initial fixation method, which is often converted to internal fixation when a wounded soldier is returned to the United States. This temporary approach to damage control is a major change from the Vietnam War, where casualties were often treated in the combat theater for weeks before being sent to the United States.

During the initial steps of the evacuation chain, spanning external fixation and a prepackaged peel pack containing a hand-

powered pin driver are used. This practice has been proven to be a safe and effective means of providing initial stabilization.<sup>36</sup> The use of external ring fixation has become common, particularly in the most severe wounds and results in low complication rates.

## Regional Anesthesia and Total Intravenous Anesthesia

Combat pain management has challenged clinicians caring for wounded warriors from the point of injury on the battlefield through MEDEVAC and even in tertiary care facilities. Suboptimal analgesia may be associated with long-term sequelae such as posttraumatic stress disorder, depression, sleep disturbances (nonrestorative sleep patterns), and chronic pain syndromes.<sup>37</sup> Recent advances have allowed patients to benefit from optimized pain control as a result of increased focus on combat pain management. Four such notable advances include the total intravenous anesthesia (TIVA) movement, the adoption of the pump for regional anesthesia, the use of oral transmucosal fentanyl citrate (OTFC), and the Military Pain Care Act.

The ability to provide TIVA significantly reduces the logistic and equipment constraints on anesthesia providers. This becomes especially important in combat and other austere medicine settings, where every effort is made to reduce the burden of required equipment and supplies. Forward surgical teams are now equipped with automated syringe infusion pumps, and staff are trained in their use as part of a balanced TIVA anesthetic. The pairing of pain pumps and regional/neuraxial anesthesia techniques is another clear example of combat pain control improvement through use of a medical force multiplier. These battlefield patient controlled analgesia pumps are routinely used to control pain in combat casualties during transport on military aircraft. Advanced regional anesthesia techniques have been extremely effective for acute pain management, especially pain from extremity injuries and rib fractures. Such techniques include continuous epidurals, continuous peripheral nerve blocks, and continuous transverses abdominis plane blocks. The advantages of regional analgesia include significant decrease in pain with profound opioid sparing.<sup>38,39</sup>

OTFC has also been used in theater. It is easily administered without need for intravenous access, and a single 400- $\mu$ g dose is more potent with more effective analgesia than 5 mg to 10 mg of morphine delivered intramuscularly. OTFC affords both quick relief from buccal absorption and prolonged relief from gastrointestinal absorption. Although respiratory depression remains a concern, combat medics devised and implemented a safety feature designed to decrease risk of narcosis by taping the stick end of the buccal lozenge to the casualty's finger, resulting in gravity-dependent withdrawal of the medication if the patient becomes oversedated.

Guiding policies and legislation often do not have as obvious or as tangible an impact as the resurgence of TIVA and regional anesthesia techniques; nevertheless, the Military Pain Care Act of 2008 prioritized pain care as a national priority and brought the focus to efforts to improve quality of analgesia. In August 2009, the Pain Management Task Force was commissioned to provide comprehensive pain management strategies. By September 2010, this team composed 109 recommendations geared toward a comprehensive pain management policy. The command guidance for prioritization of optimal pain control with

avoidance of chronic pain sequelae, combined with regional anesthesia and TIVA and target-controlled infusion technology, represents significant advances in anesthesia and pain control for the combat wounded. This will translate into improved outcomes for injured soldiers, sailors, airmen, and marines.

## Combat Burn Care

Despite many advances since the Vietnam era, few aspects related to the treatment of the burn casualty create a greater challenge for the provider than the process of resuscitation during the first 24 hours to 48 hours following injury. Military casualties with severe burns often have other injuries, and these can significantly complicate care. The challenges associated with fluid resuscitation of the military burn casualty can be greater for deployed providers, who are often unaccustomed to caring for patients with severe burns.

It is in the area of burn resuscitation that the military has made great strides in the ability to provide early resuscitation of the burn casualty. These efforts have yielded results that can be declared highly successful, if not revolutionary, in their impact.

Among the lessons learned early in the war in Iraq was that there was significant variability in the administration of fluids with overresuscitation being more common than underresuscitation, often with devastating outcomes.<sup>40</sup> This observation led to two major improvements in military burn care, implementation of the Burn Resuscitation Flow Sheet and use of a simplified formula appropriately called the Rule of Ten.<sup>41,42</sup> Observations made as part of the Joint Theater Trauma System (JTTS) performance improvement process led to creation and standardization of a simple form designed to be initiated by the initial care team and accompany the patient throughout the evacuation continuum. Documentation of fluids of all varieties and the quantities of each fluid infused allowed providers to more easily recognize the cumulative nature of the resuscitative process. This seemingly simple act proved to be a significant contributor in improving the resuscitation process.<sup>43</sup> On the coattails of the burn flow sheet came the other important change to the burn resuscitation process—development and fielding of the Rule of Ten.<sup>44</sup> The initial fluid rate is calculated by multiplying the estimated burn size (total burn surface area [TBS]) by 10 mL/h.

$$\text{Initial fluid rate} = \text{TBS} \times 10 \text{ mL/h.}$$

The Rule of Ten simplifies the calculation of an initial fluid resuscitation rate and emphasizes that fluid infusion rate needs to be adjusted based on the patient's response. Further advances related to monitoring of resuscitation continue in the form of Burn Resuscitation Decision Support System (BRDSS) software.<sup>45</sup> Computer-based tools such as BRDSS are being developed and are nearing approval from the US Food and Drug Administration (FDA) for large-scale fielding. Preliminary analysis of the effectiveness of BRDSS prototypes strongly suggests that we will see major benefit from these tools to aid burn resuscitation in the near future.

## Renal Replacement Therapy

Early and aggressive application of renal replacement therapy to support severely ill combat-injured patients with renal failure is not a new concept. The first such reports date back to

the Korean War, and this therapy is widely considered to be one of the key RMMAs in the history of combat casualty care during that conflict.<sup>46</sup> During OCOs, advances in this arena have involved the application of continuous renal replacement therapy (CRRT) in the most severely injured. The impact of acute kidney injury on mortality in patients with burn injury has been between 80% and 100% during the last few decades, even with dialysis. Not until the current OCOs has CRRT been used to address this problem. Before November 2005, only conventional hemodialysis was available for critically ill burn casualties who developed acute kidney injury, but they were not offered these services most of the time because of their hemodynamic instability. For this reason, a CRRT program was developed in November 2005 with an emphasis on continuous venovenous hemofiltration. Results were dramatic with absolute reductions in in-hospital mortality (compared with historical control) of 32% in the combat-injured patients<sup>47</sup> and 24% when combining all patients (both civilian and combat).<sup>48</sup> These observations have spawned a multicenter trial evaluating continuous venovenous hemofiltration in burns<sup>49</sup> and application and further deployment of CRRT capability in theater and Germany.<sup>50</sup>

## Burn Care

The most commonly used topical antimicrobial agents include silver sulfadiazine and sulfamylon cream.<sup>51</sup> Newer topical treatment modalities include dressings that contain silver particles within their fibers, which can release silver anions. The silver provides broad spectrum protection of the dressing against microbial contamination and serves as an antimicrobial barrier.<sup>52</sup> The ability to wrap silver-impregnated dressings on burn casualties decreases the frequency of dressing changes, which is often beneficial during the long-range transport of patients between theater and the US-based care facility. These dressings are used in combination with negative-pressure wound dressings (NPWDs) to prepare wound beds for grafting and secure grafts once in place.<sup>53</sup> NPWDs are now used at the level of the combat surgical hospital (Role 3) and beyond. This option allows surgeons to debride complex wounds, place the NPWD in the operating room, and leave it securely in place for several days if needed.

## Skin Replacement

Improvements in resuscitation and more rapid transport of burn casualties from the war zone have resulted in burn survivors with larger wounds requiring coverage. To achieve rapid wound closure for patients with full-thickness burns that do not allow immediate autologous coverage, the use of biosynthetic materials and/or cultured tissue may be beneficial.

Integra has been used as a neodermis for patients with full-thickness skin loss and can be covered with autologous skin or cultured epidermal autografts.<sup>54</sup> Cultured epidermal autografts have been used to treat several US military burn casualties with burns in excess of 85% TBS.

## Prevention

As with all traumatic injuries, effective prevention deserves our best efforts. The benefits of mitigating thermal injury cannot be overstated. Analysis of combat injuries early in the war in

Iraq and Afghanistan revealed that hand burns were among the most prevalent thermal injuries encountered. Rapid fielding of improved flame-resistant gloves showed great effectiveness in reducing hand burns and subsequent disability.<sup>55</sup> Similar improvements have been noted with the development of new flame-resistant uniforms. Issuance of the flame-resistant Army combat shirt and other uniform items was also correlated with a marked reduction in thermal injuries among deployed troops.

### Management of Traumatic Brain Injury

Traumatic brain injury (TBI) remains a common component of injury patterns encountered in modern theaters of conflict. The evolving military medical revolutions regarding this entity have involved both improved recognition of the problem and improvements in the treatment of combat-related brain injury. The spectrum of injury encountered may prove diverse, encompassing both mild and severe injury patterns with associated variability in subsequent impairment. Revolutionary efforts to improve these outcomes have included improved screening at the earliest stages after injury, resuscitative adjuncts designed to minimize secondary injury, and improved selection of operative strategies designed to optimize outcome.

### Mild TBI Screening

In 2003, as hostilities in Operation Iraqi Freedom transitioned from traditional warfare to insurgency, it became readily apparent that this new enemy tactic was producing large numbers of casualties with mild TBI (concussive brain injury).

The initial tool developed to screen for mild TBI was the military acute concussion evaluation tool. This tool was developed by the Defense and Veterans Brain Injury Center and included both a history and an evaluation component. The history component was used to requisite elements that were congruent with the potential diagnosis of mild TBI. The neurocognitive screening component of the military acute concussion evaluation was developed from the standardized assessment of concussion to assess the neurologic domains of orientation, immediate memory, concentration, and delayed recall.<sup>56,57</sup> In 2007, the JTTS published a TBI CPG based on the Defense and Veterans Brain Injury Center workgroup's consensus. After the development of a defined screening methodology, formal neurocognitive screening was introduced into the predeployment and postdeployment health assessments in 2007. In 2009, Veterans Affairs and the US Department of Defense partnered to develop a formal Defense Center of Excellence for Psychological Health and Traumatic Brain Injury with the explicit goal of fostering improvements and minimizing practice variability in the management of behavioral health and TBI.

In 2010, a directive type memorandum (DTM 09-033), "Policy Guidance for the Management of Concussion/Mild Traumatic Brain Injury in the Deployed Setting," was issued to address battlefield mild TBI, including establishment of mandatory reporting events requiring mild TBI evaluations and reporting with the ultimate goals of improving early detection, appropriate treatment, and avoidance of injury exacerbation.

### Hypertonic Saline Use in TBI

Revolutions in resuscitation have also emerged as standards of care in present OCOs. Among these changes, the use of

hypertonic saline (HTS) has, in particular, been introduced with the intent to improve TBI outcome. HTS is a particularly attractive fluid choice for patients with TBI for several reasons. It has been demonstrated that HTS may prove more effective in decreasing cerebral edema, compared with mannitol, owing to its higher osmotic reflection coefficient across the blood-brain barrier. HTS-mediated increases in capillary vessel inner diameter via dehydration of endothelial cells, coupled with decreased erythrocyte volume secondary to dehydration, may also promote increased blood flow to regions of the brain most at risk for secondary injury.<sup>58-61</sup> For this reason, the JTTS CPGs presently advocate the administration of 3% HTS in this population. Using a strict protocol approach to the use of this management adjunct, 3% HTS has been used in the OCO environment over 6 years, with no documented adverse events. Following this lead, similar successes have been reported in the civilian literature documenting the safe use of HTS among brain-injured civilians.<sup>62</sup>

### Surgical Intervention for Penetrating TBI

The appropriate management of penetrating brain injuries in the civilian trauma environment has remained an active matter of investigation.<sup>63</sup> Although some groups have proposed the benefits of aggressive policies of cranial decompression following penetrating mechanisms,<sup>64,65</sup> these procedures carry appreciable risk for complications.<sup>66</sup> The OCO care of severe TBI patients remains unique because, in this environment, decompressive interventions are more commonly required owing to the concerns of potential intracranial pressure changes during aeromedical evacuation. This requirement for more aggressive surgical approaches has, however, led to important discoveries regarding the potential impact of liberal decompression on survival after severe TBI.

In a recent study comparing civilian and military patients with severe TBI, DuBose et al.<sup>67</sup> found that matched military patients were significantly more likely to both undergo invasive intracranial monitoring (13.8% vs. 1.7%,  $p < 0.001$ ) and operative neurosurgical intervention (21.5% vs. 7.2%,  $p < 0.001$ ). Mortality was also significantly less among military casualties overall (7.7% vs. 21.0%,  $p < 0.001$ ; OR, 0.32 [95% CI, 0.16-0.61]) and particularly following penetrating mechanisms of injury (5.6% vs. 47.9%,  $p < 0.001$ ; OR, 0.07 [95% CI, 0.02-0.20]) compared with propensity score-matched civilian counterparts. This report, combined with ongoing military study, has raised awareness of the potential of aggressive decompression to improve penetrating TBI outcome in the civilian trauma environment.

### Negative-Pressure Combat Wound Dressings

Arguably, one of the most revolutionary advances in the last 20 years has been the advent of negative-pressure wound therapy (NPWT) for the management of complex wounds before definitive closure. NPWT has been reported to decrease time to closure, reduce infection, and decrease labor required for dressing changes when used in the management of complex soft tissue wounds sustained in combat.<sup>68</sup> Application of NPWT in complex contaminated soft tissue extremity injuries, even with the first debridement, owing to blast and penetrating injury as well as temporary management of complex abdominal wounds, has been

well described.<sup>22,69,70</sup> In burns, use of NPWT has improved the ability to dress wounds, prepare wound beds for grafting, and secure grafts once in place.<sup>53</sup>

NPWT dressings are now used at the level of the combat surgical hospital (Role 3) and beyond. The feasibility and safety of NPWT during global air evacuation, an important advance, has also been recently described.<sup>71</sup> A single dressing compared with the multiple wet-to-dry dressing changes is a profound change in the management of combat wounds.

### Far-Forward Minimally Invasive Surgery

Whereas military experience led to many of the advances in surgical care, the advancements made in minimally invasive surgery (MIS) developed exclusively in the civilian peacetime setting. MIS use in the evaluation of low-energy abdominal penetrating trauma developed owing to its potential time-to-recovery advantage over open technique. Based on the civilian experience, consensus was reached among a group of Air Force surgeons that MIS could offer a select population of the combat-injured or those in need of emergency general surgery a valuable surgical alternative, provided that the technology could be safely and effectively deployed, operated, and maintained in the forward environment (unpublished report, Bowers S, Bailey J, Jenkins D, The role of MIS in the forward combat hospital, 2008).

The first recorded successful minimally invasive forward operation was a laparoscopic appendectomy performed at the Air Force Theater Hospital (AFTH) in Iraq in February 2006 (Personal operating room case logs, AFTH Iraq and Craig Joint Theater Hospital, Afghanistan). Following this operation, the initial experience with forward MIS was selectively expanded to include diagnostic laparoscopy to evaluate for peritoneal penetration in fragment injury (eight, one conversion to open for positive finding), appendectomy (eight), small-bowel adhesiolysis (two), and video thoracoscopy for decortication (one) and evacuation of retained hemothorax (two). Following this initial experience, the demonstrated operability and advantage of MIS in the forward setting led to growing acceptance and formal sustaining of the capability throughout the remainder of the AFTH experience in Iraq and subsequently and to date at the Craig Joint Theater Hospital in Afghanistan.

### Thromboelastography and Rotational Thromboelastometry

Bleeding is compounded by the presence of acute traumatic coagulopathy, which is present in a quarter of casualties and quadruples mortality.<sup>72–74</sup> While the armamentarium of the clinician builds, knowing when to deploy these resources is less clear. Conventional tests of coagulation, such as prothrombin time and partial thromboplastin time, are unsuitable for directing blood product resuscitation because they take time to analyze<sup>75</sup> and provide an incomplete picture of coagulation status. This led the UK Defence Medical Service (DMS) to evaluate rotational thromboelastometry (RoTEM) for point-of-care coagulation testing.<sup>76</sup> RoTEM provides a rapid evaluation of a patient's coagulation profile, allowing clinicians to tailor resuscitation. For example, a reduction in maximum clot firmness (the amplitude of the trace) would prompt a clinician to diagnose hypocoagulability and administer plasma or platelets. In contrast, a sudden decay of an initially normal trace would suggest

hyperfibrinolysis, requiring TXA (or additional doses of TXA). Both types of patients would present with a similar clinical picture of diffuse microvascular bleeding. RoTEM is a new tool in the management of combat casualties. It requires further evaluation but may—in the near future—facilitate more targeted blood component use and reduce transfusion requirements.

## GLOBAL EN ROUTE CARE

### Critical Care Air Transport Team

Global *en route* care and the US Air Force CCATTs revolutionized combat care for the critically ill. In the Vietnam War, casualties were evacuated weeks after injury. In response to casualty evacuation issues in Somalia in 1993, the US Air Force created a CCATT to augment aeromedical evacuation crews when critically ill or injured patients were transported. The mission of the team was to manage up to three high-acuity mechanically ventilated patients or up to six less ill patients who had received initial resuscitation but remained critically ill. The team was designed to transport the traumatically injured and the medically ill. The team is composed of a physician experienced in critical care (emergency medicine, intensivist, pulmonologist, cardiologist, or anesthesiologist), a respiratory therapist, and a critical care nurse. The team assumes care of the patient at a Level II or Level III theater hospital and manages the patient until arrival at the receiving hospital. The CCATT is equipped to care for patients and to diagnose and treat uncommon complications such as acute hypoxia, respiratory failure, pneumothorax, and shock. Flights range from 1 hour (intratheater) to 18 hours (transatlantic flights) and are commonly 6 hours to 8 hours long. In the Vietnam War, patients would be evacuated from theater to a remote hospital in 21 days; with the CCATTs, the average movement from injury is 28 hours and is frequently as few as 12 hours.<sup>77,78</sup> CCATT is considered one of the most important contributions to survival in Operation Iraqi Freedom and Operation Enduring Freedom.<sup>77</sup>

Since the beginning of Operation Enduring Freedom and Operation Iraqi Freedom, approximately 16,000 missions have flown with 8,000 patients.<sup>79</sup> Most patients are traumatically injured (40–65%), and the remaining are medically ill. Approximately 50% are ventilated mechanically, 10% receive vasoactive infusions, and 6% receive blood products in flight. Reversible hypotension and hypoxia are the most common complications. Death, in-flight endotracheal intubations, and chest thoracostomy placements or flight diversions are rare.<sup>78–80</sup> In addition to combat theater evacuations, the CCATT model has been used to develop the Acute Lung Rescue Team, a team with more advanced training and equipment for transporting patients with severe acute lung injury.

### Burn Transport

US military medical crews capable of transporting critically injured burn casualties include the Air Force CCATT and the Army's Burn Flight Team (BFT). Both teams are capable of transporting severely burned casualties autonomously, and both routinely use the transport capabilities of the C17 Globemaster III tactical transport aircraft.

The Army's BFT flight mission is generally performed by five personnel: a critical care surgeon, a registered nurse, a licensed

vocational nurse, a respiratory therapist, and an operations non-commissioned officer. The size and composition of a deploying team is easily adjusted according to the number and complexity of the patients being transported. Patients with burn injury are evacuated from the operational theater to Landstuhl Regional Medical Center in Germany. From here, war casualties requiring care in a burn center are transported from Landstuhl Regional Medical Center to the USAISR Burn Center at San Antonio Military Medical Center at Fort Sam Houston, an 8,000 mile evacuation lasting approximately 16 hours in flight.

Since 2003, critically ill and injured casualties are transported both safely and expeditiously, usually arriving in a US-based medical center as soon as 3 days to 4 days following injury. This revolutionary change to definitive early care provided at the USAISR Burn Center (verified by the American Burn Association) leverages technological advances, which increase medical capabilities during transport. With these technologies, the BFT can provide ventilator support, advanced monitoring, state-of-the-art fluid resuscitation, and clinical laboratory testing. This ability to monitor blood physiology and organ function (e.g., heart, lung, liver, and kidney) and cardiovascular dynamics is lifesaving. With these capabilities, patients can be safely transported as a result of this ability to practice “critical care in the air.”

### En Route Critical Care Nursing

For the first time in history, military nurses have been dedicated to the mission of rotary wing critical care transport during combat. Flight nurses were a significant part of the military medical team and the fixed-wing transport system, which continued beyond World War II into the Korean and Vietnam wars before OCOs. Before 2010, flight medics assigned to aviation units and physicians and nurses assigned to deployed hospitals would often transport significantly injured trauma patients who had recently undergone DCR and initial operations to manage their wounds. The nurses and physicians were selected for the missions on the basis of their experience and training. For those patients requiring more specialized care and accompaniment by a nurse or a physician, that health care provider was removed from the team or hospital, sometimes for several days.<sup>81–83</sup> Their removal proved particularly problematic in Afghanistan, leaving remote facilities with few personnel, making it difficult to send nurses or physicians with critically ill or injured patients. In 2010, the US Army Nurse Corps dedicated a team of critical care nurses to the mission of *en route* care for transport to Role 3 care in Afghanistan. The *en route* critical care nurses are now embedded in the aviation units and provide specialized care to the combat wounded.<sup>84</sup> This has given nurses a unique opportunity to collaborate with our out-of-hospital providers (Fig. 2). This was done routinely in Iraq by 2006, with nurses from US Navy, US Air Force, and US Army transporting patients from Level II to III and between Level III facilities.

### US Army Flight Medic Training

Military physicians have long recognized that rapid evacuation from the battlefield decreases suffering and prevents death. Helicopter MEDEVAC underwent a significant expansion and growth during the Vietnam era. The success of military casualty care led to the passage of the National Highway Safety Act and prompted Congress to fund the development of our modern

civilian emergency medical services (EMS) systems. Coincident with the development of modern civilian EMS systems were the end of the Vietnam War and the demobilization of the physicians, nurses, and medics who served. Many of these returning medical providers helped develop the current EMS systems based on their wartime experiences.

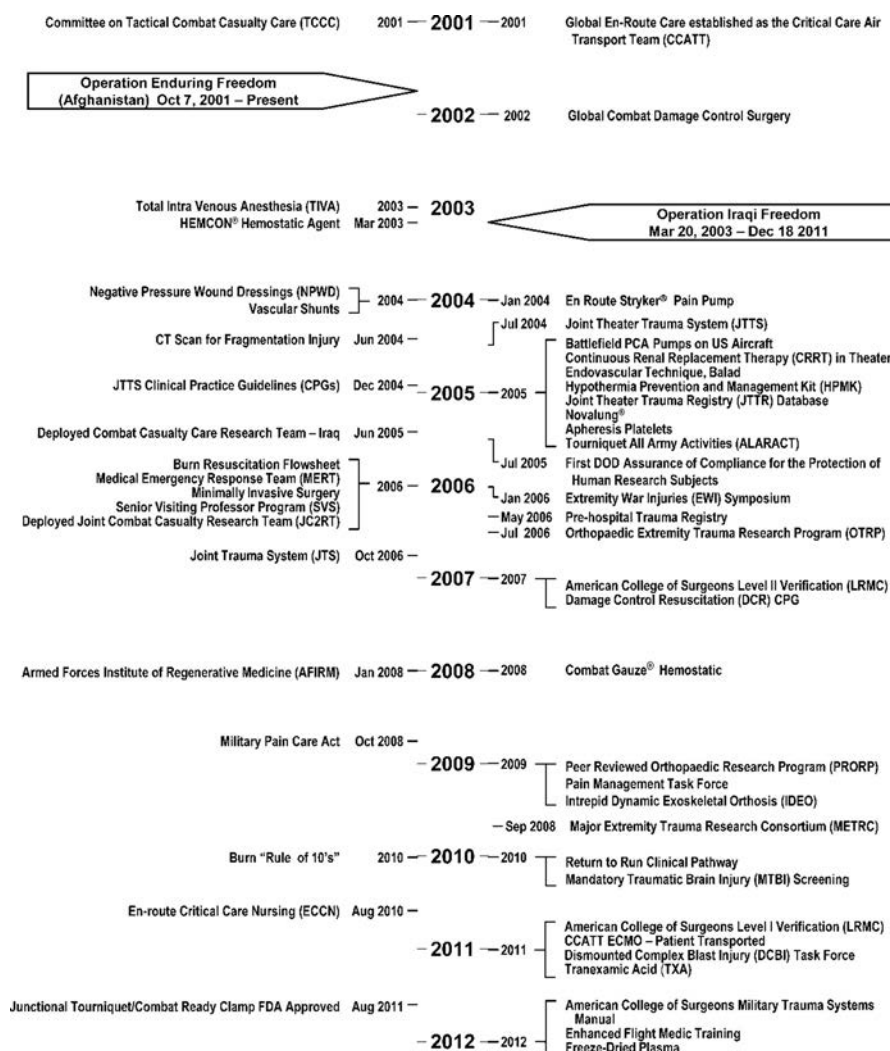
The civilian model evolved to become patient centric, focusing on care delivered *en route* and training providers to a high level to provide that care in the unique environment of the helicopter. The US Army's model remained platform centric, focusing on the aircraft's performance and operations. *En route* care in the Army was still provided by a single combat medic with basic emergency medical technician capability, essentially in the same fashion as it was done during the Vietnam War. Thus, civilian EMS developed as a sophisticated system, with aircraft generally staffed by a pair of highly trained flight paramedics and/or flight nurses, whereas the US Army staffs its MEDEVAC helicopters with a single EMT-Basic despite a contemporary operational environment requiring (1) transport of unprecedented numbers of civilians, including pediatric, geriatric, obstetric, and medical cases; (2) transport of postoperative critical care patients between facilities; and (3) transport across large geographic areas requiring prolonged in-flight care.

A recent study compared patient outcomes between casualties evacuated by the conventional Army MEDEVAC system and an Army National Guard MEDEVAC unit staffed by critical care trained flight paramedics using protocols and staffing models adopted for the combat environment based on current civilian helicopter EMS practice in the United States.<sup>85</sup> The National Guard unit using a civilian Helicopter Emergency Medical Service model was associated with a 66% reduction in the risk of death at 48 hours among severely injured casualties (Injury Severity Score [ISS] >16). This study, along with numerous After Action Reports from deployed units citing the need for an increased level of training for flight medics, prompted the Army Medical Department to review its current flight medic training program and to initiate a new program to train all flight medics to the civilian flight paramedic standard by 2017.



**Figure 2.** CPT April Ritter (left), *en route* critical care nurse, and a flight medic assigned to the C/3-82 Dustoff out of Jalabad, Afghanistan, on a critical care transport mission.





**Figure 3.** Timeline of major military medical advances in the past decade.

This three-phase program includes an accredited paramedic program that will culminate in the National Registry of Emergency Medical Technicians (EMTs) paramedic examination and critical care training. This 9-month training program will prepare the candidates to pass the Flight Paramedic Certification examination and to deploy overseas, where they will be expected to provide care for the full spectrum of casualties being evacuated by helicopter. The role of critical care flight paramedics or other advanced medical providers in TACEVAC platforms has also been endorsed by the DHB (DHB TACEVAC memo).

## CONCLUSION

From a historical standpoint, the medical care advances in combat casualty care during the past decade have been monumental (Fig. 3). As Dr. Churchill insightfully noted more than a half a century ago, most of the combat evidence is retrospective observational data: "Cobwebs of theory and hypothesis were swept away by simple observation and precise definitions," for

we cannot apply the stringent scientific method needed to advance many of these areas and gain FDA approval from studies on the battlefield.<sup>86</sup>

The challenge going forward will be to maintain the motivation and momentum to complete the evolving and nascent RMMAs and to receive FDA approval for new innovations so that we can deploy these new capabilities and, thus, optimize the care of combat wounded in future conflicts.

## AUTHORSHIP

L.H.B. was responsible for the concept and design of this article, compilation of the text, figure and table composition, and extensive reviews. All authors listed contributed a section, with references, in their area of expertise and reviewed the article. In addition, D.G.B. and B.J.E. provided extensive reviews of the article.

## ACKNOWLEDGMENTS

We thank Ms. Otilia Sánchez for the expert editorial support and to Mr. Glen Gueller for the expert graphics support.

## DISCLOSURE

No funding was received from the National Institutes of Health, Well come Trust, or Howard Hughes Medical Institute.

## REFERENCES

1. Rotondo MF, Schwab CW, McGonigal MD, et al. Damage control: an approach for improved survival in exsanguinating penetrating abdominal injury. *J Trauma*. 1993;35:375-383.
2. Rosenfeld JV. Damage control neurosurgery. *Injury*. 2004;35:655-660.
3. Hildebrand F, Giannoudis P, Krettek C, et al. Damage control: extremities. *Injury*. 2004;35:678-689.
4. De Waele JJ, Vermassen FE. Coagulopathy, hypothermia and acidosis in trauma patients: the rationale for damage control surgery. *Acta Chir Belg*. 2002;102:313-316.
5. Blackbourne LH. Combat damage control surgery. *Crit Care Med*. 2008;36(Suppl 7):S304-S310.
6. Holcomb JB, Jenkins D, Rhee P, Johannigman J, Mahoney P, Mehta S, Cox ED, Gehrke MJ, Beilman GJ, Schreiber M, et al. Damage control resuscitation: directly addressing the early coagulopathy of trauma. *J Trauma*. 2007;62:307-310.
7. Duchesne JC, Hunt JP, Wahl G, Marr AB, Wang YZ, Weintraub SE, Wright MJ, McSwain NE Jr. Review of current blood transfusions strategies in a mature Level I trauma center: were we wrong for the last 60 years? *J Trauma*. 2008;65:272-276; discussion 276-278.
8. Damage Control Resuscitation at Level IIb/III Treatment Facilities. Available at: [http://www.usaisr.amedd.army.mil/cpgs/Damage Control Resuscitation](http://www.usaisr.amedd.army.mil/cpgs/Damage%20Control%20Resuscitation) 10 Aug 11.pdf. Accessed 6/21/2012.
9. Morrison JJ, Dubose JJ, Rasmussen TE, Midwinter MJ. Military application of tranexamic acid in trauma emergency resuscitation (MATTERS) study. *Arch Surg*. 2012;147:113-119.
10. Leppaniemi A. Abdominal war wounds: experiences from Red Cross field hospitals. *World J Surg*. 2005;29:S67-S71.
11. Demetriades D, Velmos G. Technology-driven triage of abdominal trauma: the emerging era of nonoperative management. *Ann Rev Med*. 2003;54:1-15.
12. *Emergency War Surgery*. Szul AC, Davis LB, eds. Walter Reed Army Medical Center: Borden Institute. Third United States Revision, 2004.
13. Beekley A, Blackbourne L, Sebesta J, McMullin N, Mullenix P, Holcomb J. Selective nonoperative management of penetrating torso injury from combat fragmentation wounds. *J Trauma*. 2008;64:S108-S117.
14. White JM, Stannard A, Burkhardt GE, Eastridge BJ, Blackbourne LH, Rasmussen TE. The epidemiology of vascular injury in the wars in Iraq and Afghanistan. *Ann Surg*. 2011;253:1184-1189.
15. Clouse WD, Rasmussen TE, Peck MA, et al. Current in theater management of wartime vascular injury: a report from Operation Iraqi Freedom. *J Am Coll Surg*. 2007;204:625-632.
16. Stannard A, Brown K, Benson C, Clasper J, Midwinter M, Tai NR. Outcome after vascular trauma in a deployed military trauma system. *Br J Surg*. 2011;98:228-234.
17. Rich NM, Hughes CW, DeBakey ME. Recognition of Air Force surgeons at Wilford Hall Medical Center supported 332nd Air Force Theater Hospital, Balad Air Base Iraq. *J Vasc Surg*. 2007;46:1312-1313.
18. Burkhardt GE, Gifford SM, Propper BW, et al. The impact of ischemic interval on neuromuscular recovery in a porcine (Sus Scrofa) survival model of extremity vascular injury. *J Vasc Surg*. 2011;53:165-173.
19. Hancock HM, Stannard A, Burkhardt GE, et al. Hemorrhagic shock worsens neuromuscular recovery in a porcine model of hind limb vascular injury and ischemia/reperfusion. *J Vasc Surg*. 2011;53:1052-1062.
20. Woodward EB, Clouse WD, Eliason JE, et al. Penetrating femoropopliteal injury during modern warfare: experience of the Balad vascular registry. *J Vasc Surg*. 2008;47:1259-1265.
21. Gifford SM, Aidinian G, Clouse WD, et al. Effect of temporary vascular shunting on extremity vascular injury: an outcome analysis from the GWOT vascular initiative. *J Vasc Surg*. 2009;50:549-555.
22. Quan RW, Gillespie DL, Stuart RP, et al. The effect of vein repair on the risk of venous thromboembolic events: a review of more than 100 traumatic military venous injuries. *J Vasc Surg*. 2008;47:571-577.
23. Burkhardt GE, Cox M, Clouse WD, et al. Outcomes of selective tibial artery repair following combat-related extremity injury. *J Vasc Surg*. 2010;52:91-96.
24. Peck MA, Clouse WD, Cox MW, et al. The complete management of traumatic vascular injury in a local population during Operation Iraqi Freedom: a wartime report from the 332nd EMDG/Air Force Theater Hospital Balad, Iraq. *J Vasc Surg*. 2007;45:1147-1205.
25. Leininger BE, Rasmussen TE, Smith DL, et al. Experience with wound VAC and delayed primary closure of contaminated soft tissue injuries in Iraq. *J Trauma*. 2006;61:1207-1211.
26. Rasmussen TE, Clouse WD, Jenkins DH, et al. The use of temporary vascular shunts as a damage control adjunct in the management of wartime vascular injury. *J Trauma*. 2006;61:15-21.
27. Taller J, Kamdar JP, Greene JA, et al. Temporary vascular shunts as initial treatment of proximal extremity vascular injuries during combat operations: the new standard of care at Echelon II facilities? *J Trauma*. 2008;65:595-603.
28. Gifford SM, Eliason JL, Clouse WD, et al. Early versus delayed restoration of flow with temporary vascular shunt reduces circulating markers of injury in a porcine model. *J Trauma*. 2009;67:259-265.
29. Propper BW, Alley JB, Gifford SM, et al. Endovascular treatment of blunt aortic injury in Iraq: extension of innovative endovascular capabilities to the modern battlefield. *Ann Vasc Surg*. 2009;23:687.
30. Rasmussen TE, Clouse WD, Peck MA, et al. The development and implementation of endovascular capabilities in wartime. *J Trauma*. 2008;64:1169-1176.
31. White JM, Cannon JW, Stannard A, et al. Endovascular balloon occlusion of the aorta is superior to resuscitative thoracotomy with aortic clamping in a porcine model of hemorrhagic shock. *Surgery*. 2011;150:400-409.
32. Stannard A, Eliason JE, Rasmussen TE. Resuscitative endovascular balloon occlusion of the aorta (REBOA) as an adjunct for hemorrhagic shock. *J Trauma*. 2011;71:1869-1872.
33. Avaro JP, Mardelle V, Roch A, et al. Forty minute endovascular aortic occlusion increases survival in an experimental model of uncontrolled hemorrhagic shock caused by abdominal trauma. *J Trauma*. 2011;71:720-726.
34. Owens BD, Kragh JF, Macaitis J, et al. Characterization of extremity wounds in Operation Iraqi Freedom and Operation Enduring Freedom. *J Orthop Trauma*. 2007;21:254-257.
35. Scalea TM, Boswell SA, Scott JD, et al. External fixation as a bridge to intramedullary nailing for patients with multiple injuries and with femur fractures: damage control orthopaedics. *J Trauma*. 2000;48:613-623.
36. Possley DR, Burns TC, Stinner DJ, et al. Temporary external fixation is safe in a combat environment. *J Trauma*. 2010;69:S135-S139.
37. Buckenmaier C, Rupprecht C, McKnight G, McMillan B, White R, Gallagher R, Polomano R. Pain following battlefield injury and evacuation: a survey of 110 casualties from the wars in Iraq and Afghanistan. *Pain Med*. 2009;10:1487-1496.
38. Allcock E, Spencer E, Frazer R, Applegate G, Buckenmaier C. Continuous transversus abdominis plane (TAP) block catheters in a combat surgical environment. *Pain Med*. 2010;11:1426-1429.
39. Stojadinovic A, Auton A, Peoples GE, McKnight G, Shields C, Croll S, Bleckner L, Winkley J, Maniscalco-Theberge M, Muckenmaier C. Responding to challenges in modern combat casualty care: innovative use of advanced regional anesthesia. *Pain Med*. 2006;7:330-338.
40. Chung KK, Wolf SE, Cancio LC, Alvarado R, Jones JA, McCordle J, King BT, Barillo DJ, Renz EM, Blackbourne LH. Resuscitation of severely burned military casualties: fluid begets more fluid. *J Trauma*. 2009;67:231-237; discussion 237.
41. Chung KK, Blackbourne LH, Wolf SE, et al. Evolution of burn resuscitation in operation Iraqi freedom. *J Burn Care Res*. 2006;27:606-611.
42. Kauvar DS, Wolf SE, Wade CE, et al. Burns sustained in combat explosions in Operations Iraqi and Enduring Freedom (OIF/OEF explosion burns). *Burns*. 2006;32:853-857.
43. Ennis JL, Chung KK, Renz EM, et al. Joint Theater Trauma System implementation of burn resuscitation guidelines improves outcomes in severely burned military casualties. *J Trauma*. 2008;64(Suppl 2):S146-S151; discussion 151-152.

44. Chung KK, Salinas J, Renz EM, et al. Simple derivation of the initial fluid rate for resuscitation of severely burned adult combat casualties: in silico validation of the rule of 10. *J Trauma*. 2010;69:S49 S54.
45. Salinas J, Chung KK, Mann EA, et al. Computerized decision support system improves fluid resuscitation following severe burns: an original study. *Crit Care Med*. 2011;39:2031 2038.
46. Chung KK, Perkins RM, Oliver JD. Renal replacement therapy in support of combat operations. *Crit Care Med*. 2008;36:S365 S369.
47. Chung KK, Juncos LA, Wolf SE, et al. Continuous renal replacement therapy improves survival in severely burned military casualties with renal failure. *J Trauma*. 2008;64:S179 S185.
48. Chung KK, Lundy JB, Matson JR, et al. Continuous venovenous hemofiltration in severely burned patients with acute kidney injury: a cohort study. *Crit Care*. 2009;13:R62.
49. Chung K. Hemofiltration in burns: RESCUE [ClinicalTrials.gov]. September 30, 2012. Available at: <http://clinicaltrials.gov/ct2/show/NCT01213914>. Accessed January 12, 2012.
50. Cannon JW, Zonies DH, Benfield RJ. Advanced en-route critical care during combat operations. *Bull Am Coll Surg*. 2011;96:21 29.
51. Manof WW, West MA. Current treatment recommendations for topical burn therapy. *Drugs*. 1990;40:364 373.
52. Huckfeldt R, Flick AB, Mikkelsen D, et al. Wound closure after splint thickness grafting is accelerated with the use of continuous direct anodal microcurrent applied to silver nylon wound contact dressings. *J Burn Care Res*. 2007;28:703 707.
53. Petkar KS, Dhanraj P, Kingsly PM, et al. A prospective randomized controlled trial comparing negative pressure dressing and conventional dressing methods on split thickness skin grafts in burned patients. *Burns*. 2011;37:925 929.
54. Heimbach D, Luteran A, Burke J, et al. Artificial dermis for major burns. A multi-center randomized clinical trial. *Ann Surg*. 1988;208:313 320.
55. Hedman TL, Renz EM, Richard RL, Quick CD, Dewey WS, Barillo DJ, Cancio LC, Baer DG, Wolf SE, Holcomb JB. Incidence and severity of combat hand burns after all army activity message. *J Trauma*. 2008;64(Suppl 2):S169 S172; discussion S172 S173.
56. Coldren RL, Kelly MP, Parish RV, Dretsch M, Russell ML. Evaluation of the military acute concussion evaluation for use in combat operations more than 12 hours after injury. *Mil Med*. 2010;175:477 481.
57. Jaffee MS, Helmick KM, Girard PD, Meyer KS, Dinegar K, George K. Acute clinical care and care coordination for traumatic brain injury within Department of Defense. *J Rehab Res Dev*. 2009;46:655 666.
58. Himmelseher S, Donaldson K, Loftus CM, Jallo J. Hypertonic saline solutions for treatment of intracranial hypertension. *Curr Opin Anaesthesiol*. 2007;20:414 426.
59. Tyagi R, et al. Hypertonic saline: a clinical review *Neurosurg Rev*. 2007;30:277 289.
60. Bratton SL, Chestnut RM, Ghajar J, Hammond FFM, Harris OA, Hartl R, Manley GT, Nemecek A, Newell DW, Rosenthal G, et al. Hyperosmolar therapy. *J Neurotrauma*. 2007;24(Suppl 1):S14 S20.
61. Pascual JL, et al. Resuscitation of hypotensive head-injured patients: is hypertonic saline the answer? *Am Surg*. 2008;74:253 259.
62. DuBose J, Kobayashi L, Lozornio A, Teixeira P, Inaba K, Lam L, Talving P, Branco B, Demetriades D, Rhee P. Clinical experience using 5% hypertonic saline as a safe alternative fluid for use in trauma. *J Trauma*. 2010;68:1172 1177.
63. Li LM, Timofeev I, Czosnyka M, Hutchinson PJA. The surgical approach to the management of increased intracranial pressure after traumatic brain injury. *Anesth Analg*. 2010;111:736 748.
64. Howard JL, Cipolle MD, Anderson M, Sabella V, Shollenberger D; Li PM, Pasquale MD. Outcome After decompressive craniectomy for the treatment of severe traumatic brain injury. *J Trauma*. 2008;65:380 385; discussion 385 386.
65. Schirmer CM, Ackil AA Jr, Malek AM. Decompressive craniectomy. *Neurocrit Care*. 2008;8:456 470.
66. Stiver SI. Complications of decompressive craniectomy for traumatic brain injury. *Neurosurg Focus*. 2009;26:E7.
67. DuBose JJ, Barmparas G, Inaba K, et al. Isolated severe traumatic brain injuries sustained during combat operations: demographics, mortality outcomes and lessons to be learned from contrasts to civilian counterparts. *J Trauma*. 2011;70:11 16; discussion 16 18.
68. Hinck D, Franke A, Gatzka F. Use of vacuum-assisted closure negative pressure wound therapy in combat-related injuries literature review. *Mil Med*. 2010;175:173 181.
69. Powell ET. The role of negative pressure wound therapy with reticulated open cell foam in the treatment of war wounds. *J Orthop Trauma*. 2008;22:S138 S141.
70. Geiger S, McCormick F, Chou R, Wandel AG. War wounds: lessons learned from Operation Iraqi Freedom. *Plast Reconstr Surg*. 2008;122:146 153.
71. Fang R, Dorlac WC, Flaherty SF, et al. Feasibility of negative pressure wound therapy during intercontinental aeromedical evacuation of combat casualties. *J Trauma*. 2010;69:S140 S145.
72. Niles SE, McLaughlin DF, Perkins JG, Wade CE, Li Y, Spinella PC, et al. Increased mortality associated with the early coagulopathy of trauma in combat casualties. *J Trauma*. 2008;64:1459 1463.
73. Brohi K, Cohen MJ, Ganter MT, Schultz MJ, Levi M, Mackersie RC, et al. Acute coagulopathy of trauma: hypoperfusion induces systemic anticoagulation and hyperfibrinolysis. *J Trauma*. 2008;64:1211 1217.
74. Hess JR, Brohi K, Dutton RP, Hauser CJ, Holcomb JB, Kluger Y, et al. The coagulopathy of trauma: a review of mechanisms. *J Trauma*. 2008;65:748 754.
75. Martini WZ, Cortez DS, Dubick MA, Park MS, Holcomb JB. Thrombelastography is better than PT, aPTT, and activated clotting time in detecting clinically relevant clotting abnormalities after hypothermia, hemorrhagic shock and resuscitation in pigs. *J Trauma*. 2008;65:535 543.
76. Doran CM, Woolley T, Midwinter MJ. Feasibility of using rotational thromboelastometry to assess coagulation status of combat casualties in a deployed setting. *J Trauma*. 2010;69:S40 S48.
77. Johannigman JA. Maintaining the continuum of en route care. *Crit Care Med*. 2008;36(Suppl 7):S377 S382.
78. Mason PE, Eadie JS, Holder AD. Prospective observational study of United States (US) Air Force Critical Care Air Transport team operations in Iraq. *J Emerg Med*. 2011;41:8 13.
79. Beninati W, Lairet J, King J, et al. Short term outcomes of US Air Force Critical Care Air Transport Team (CCATT) patients evacuated from a combat setting between 2007 and 2008. *Chest*. 2009;136:28S g-28S.
80. Renz EM, Cancio LC, Barillo DJ, et al. Long range transport of war-related burn casualties. *J Trauma*. 2008;64(Suppl 2):S136 S144; discussion S144 135.
81. Higgins RA. MEDEVAC critical care transport from the battlefield. *AACN Adv Crit Care*. 2010;21:288 297.
82. Hudson TL, Morton R. Critical care transport in a combat environment: building tactical trauma transport teams before and during deployment. *Crit Care Nurse*. 2010;30:57 66.
83. Lehmann R, Oh J, Killius S, Cornell M, Furay E, Martin M. Interhospital patient transport by rotary wing aircraft in a combat environment: risks, adverse events, and process improvement. *J Trauma*. 2009;66(Suppl 4):S31 S36.
84. Nessen SC, Cronk DR, Edens J, Eastridge BJ, Little TR, Windsor J, Blackbourne LH, Holcomb JB. US Army tow-surgeon teams operating in remote Afghanistan an evaluation of split-based forward surgical team operations. *J Trauma*. 2009;66(Suppl 4):S37 S47.
85. Mabry R, Apodaca A, Penrod J, et al. Impact of critical care trained flight paramedics on casualty survival during helicopter evacuation in the current war in Afghanistan. *J Trauma*. 2012;73:S32 S37.
86. Board for the Study of the Severely Wounded. *The Physiologic Effects of Wounds*. Washington, DC: Office of the Surgeon General; 1952.